Human-Directed vs. Autonomous UAV-Based Surveillance

Michael Freed
Computational Sciences Division
Ames Research Center, CA
Michael.A.Freed@nasa.gov
(650) 604-5975

Michael G. Shafto
Computational Sciences Division
Ames Research Center, CA
Michael.G.Shafto@nasa.gov
(650) 604-6170

M. Whalley
Army/NASA Rotorcraft Division
NASA Ames Research Center, CA

Dr. M. Takahashi
QSS, Army/NASA Rotorcraft Division
NASA Ames Research Center, CA

Dr. A. Patterson-Hine
Computational Sciences Division
NASA Ames Research Center, CA

G. Schulein
SJSU, Army/NASA Rotorcraft Division
NASA Ames Research Center, CA

R. Harris
QSS, Computational Sciences Division
NASA Ames Research Center, CA

J. Howlett
SJSU, Army/NASA Rotorcraft Division
NASA Ames Research Center, CA

C. Frost
Army/NASA Rotorcraft Division
Ames Research Center, CA

- Autonomous Rotorcraft Project
- Surveillance problem definition and performance analysis tool
- Study comparing human/ algorithm performance
- Lessons for role allocation

Army/NASA Autonomous Rotorcraft Project

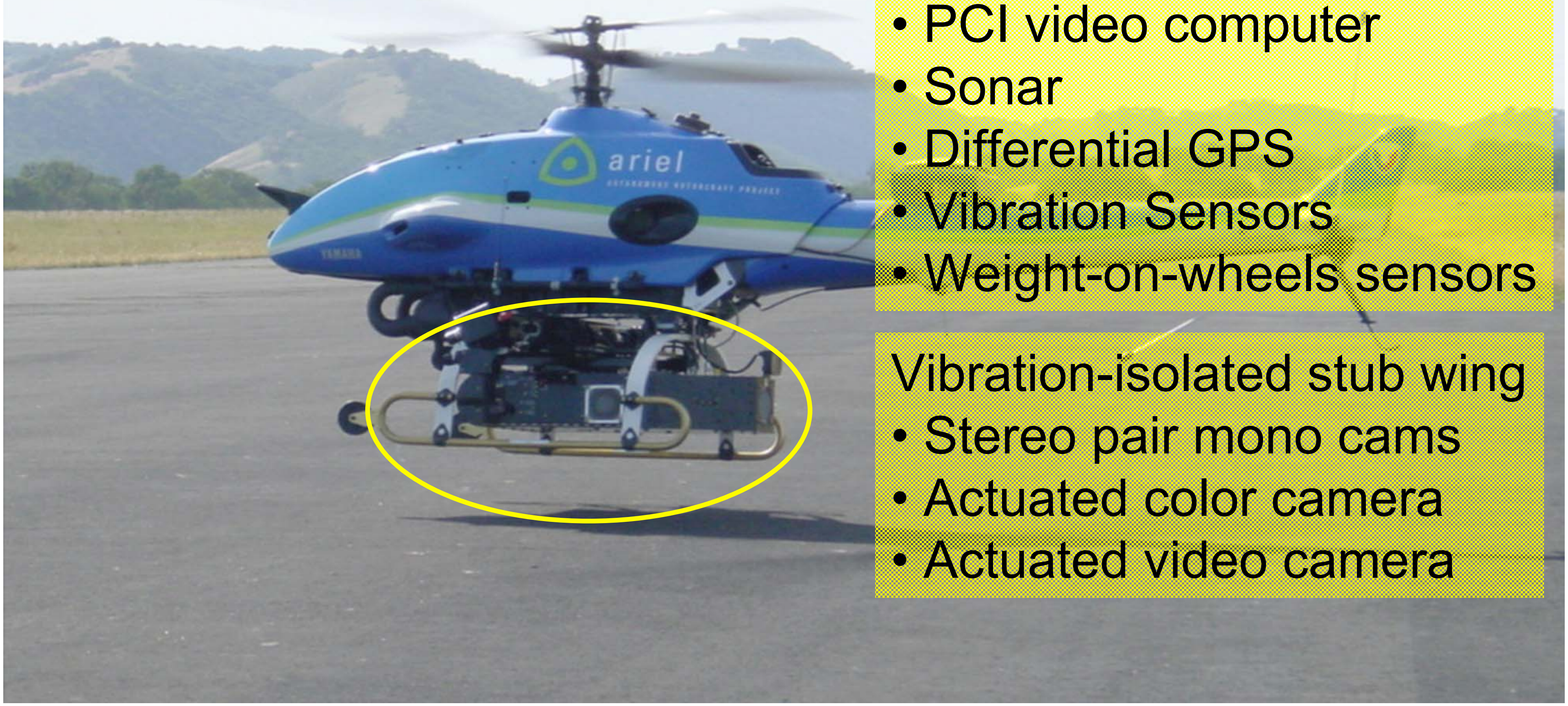
OBJECTIVE: versatile, practical and inexpensive airborne observation platform effective for a broad range of missions

Hardware - Yamaha RMAX

- 184 lb GW, 65 lb payload
- 3 m rotor diameter
- One hour endurance
- $86,000

Hardware - Yamaha RMAX

- 184 lb GW, 65 lb payload
- 3 m rotor diameter
- One hour endurance
- $86,000



Avionics Payload

- Crossbow IMU
- Radio modem
- PC104+ flight computer
- PCI video computer
- Sonar
- Differential GPS
- Vibration Sensors
- Weight-on-wheels sensors

Vibration-isolated stub wing

- Stereo pair mono cams
- Actuated color camera
- Actuated video camera

Software - Flight Control System

Model-following control law

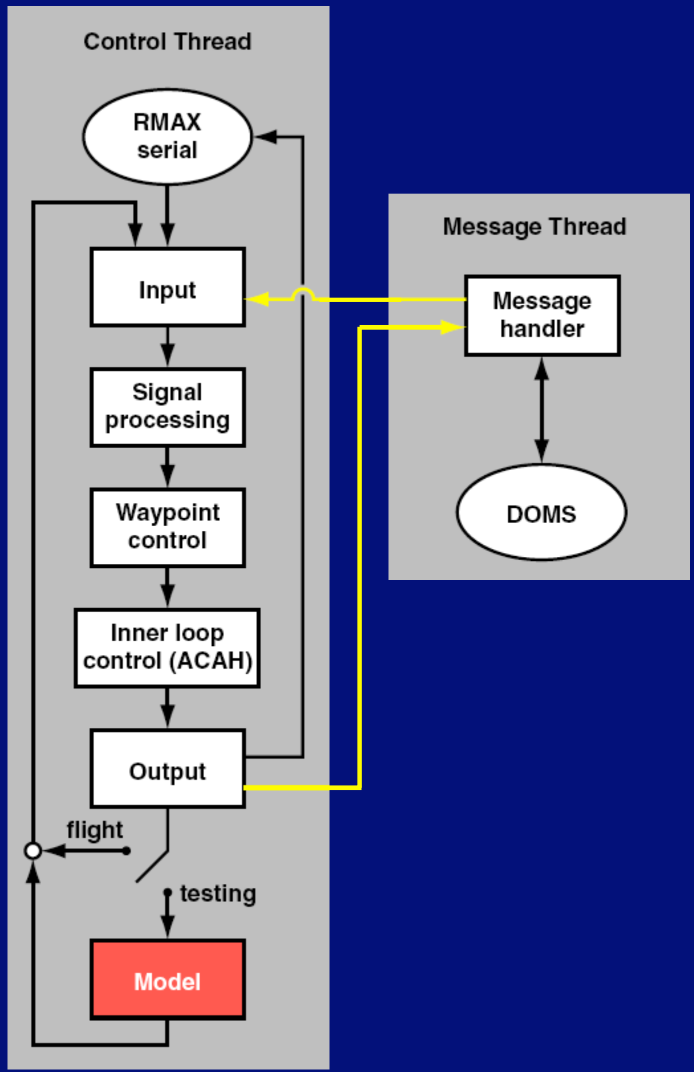
- attitude stabilization, waypoint guidance
- maintains independent heading modes

Path smoothing

- Kochanek-Bartels cubic spline fit on-the-fly within pre-defined safe corridor
- Speed profile to respect pre-defined pitch, bank angle, and climb/descent rate limits

Common code used in simulation, hardware-in-the-loop, and flight

- Embedded high-fidelity linear model enables closed-loop testing of all build types



Software - Autonomy Architecture

Apex

Deliberative Layer
(planning, scheduling)

— Surveillance scheduling

Execution Layer
(High-level control)

- Tactical sensor positioning
- Human interaction management
- Monitoring and anomaly-handling
- Obstacle avoidance path planning
- Flight patterns

Skill Layer
(sensing, actuation)

— Flight controls

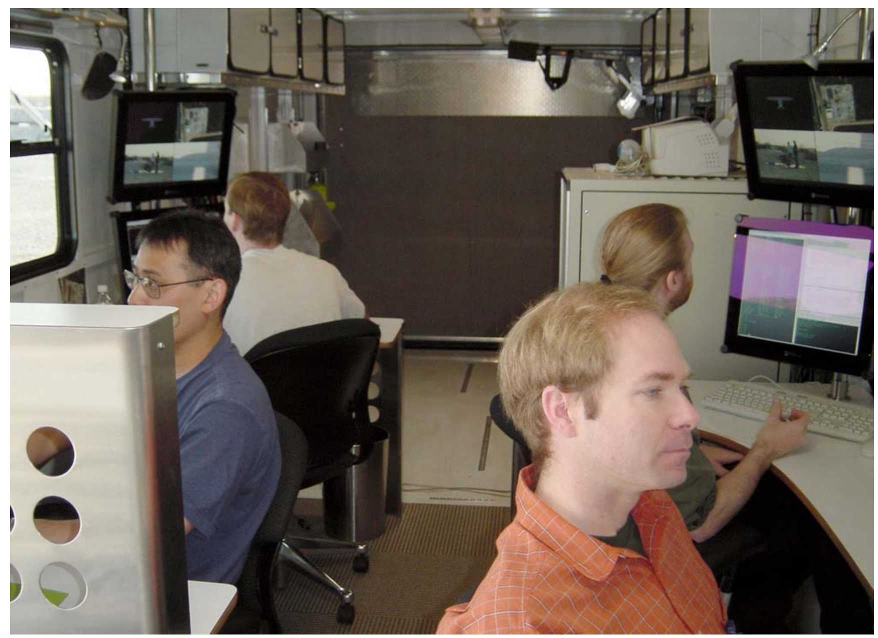
3-Tier Agent Architecture

Command Trailer

- Transports rotorcraft
- Contains workstations, comm, telemetry, weather station, tracking camera…

Surveillance Missions

- Mission operator enters targets of interest (TOIs) and target characteristics
- May intercede during autonomous operations
- Autonomous system may ask for guidance



Why Focus on Surveillance?

- Acknowledged as a critical function in diverse operational environments:
  - Military (battlespace awareness)
  - Security
  - Land management
  - Earth and planetary science
- Current practice unsatisfactory
- Autonomy achievable with current technology

The Surveillance Problem

Example Scenario

Area of operations

Valuable Assets

- **docks**
- **warehouses**
- **lighthouse**
- **orchard tract**

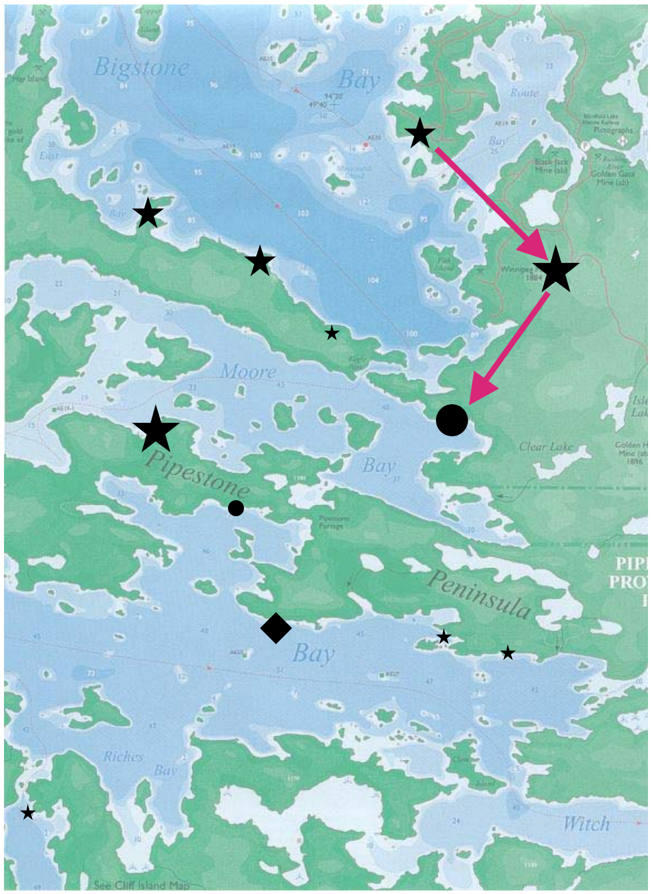
Risk: any asset can start on fire at any time

UAV Goal: do a good job detecting fires and mitigating losses

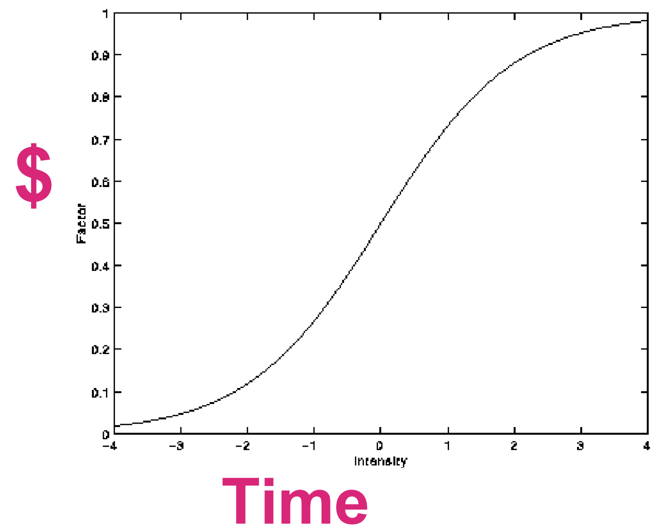
What does it mean to do a good job at surveillance in this kind of scenario?

The Surveillance Problem

Surveillance Performance Factors



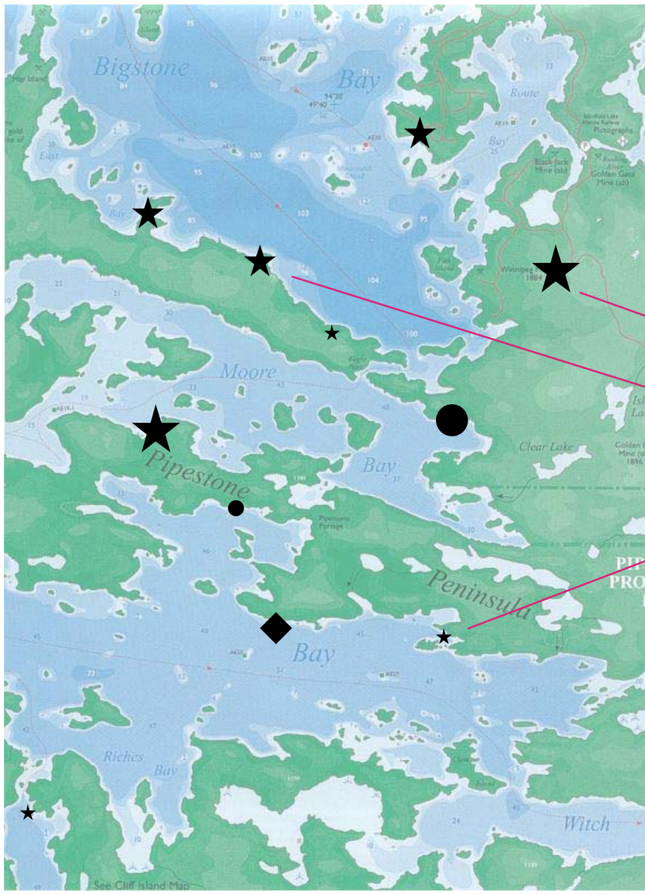
The more often a target is visited the better.



⇨ **fly efficient routes to observe targets as frequently as possible**

The Surveillance Problem

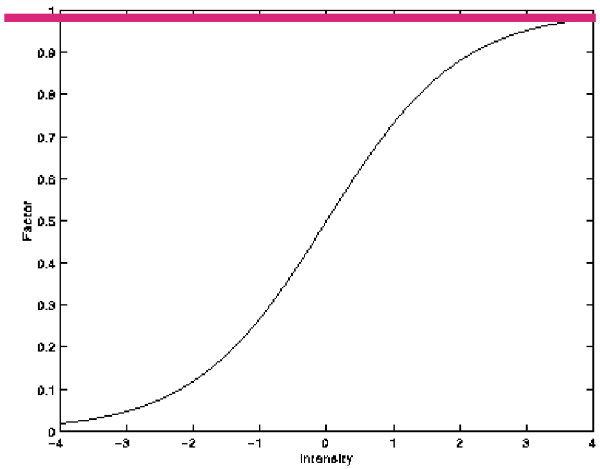
Surveillance Performance Factors



Some targets are more valuable than others

$5M
$2M
$1M

max cost



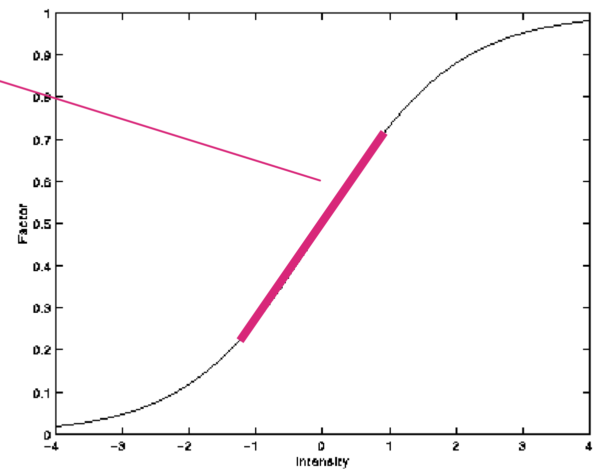
⇨ **Visit some targets more often than others**
⇨ **Possibly skip some entirely**

The Surveillance Problem

Surveillance Performance Factors

Some targets accumulate cost (burn) faster than others

rate



stone
wood
mixed

remote, unimportant, needy

- ⇨ **Visit some targets more often than others**
- ⇨ **Possibly skip some entirely**

The Surveillance Problem

Surveillance Performance

Other potentially important factors

- probability of occurrence
- detection latency
- communication latency
- intervention latency
- repeatability / concurrency

Measuring Surveillance Performance

Objectives

- Guide surveillance algorithm development
- Runtime selection of best algorithm
- *Variable autonomy**: dynamically adjust roles of human and AI in surveillance decision-making

* *For more detailed treatment, see Variable Autonomy session this afternoon including talk by Barney Pell*

Measuring Surveillance Performance

Goal of surveillance is to:

minimize the total expected cost of ignorance for all targets in the operational area over a specified mission time interval

<u>Expected Cost of Ignorance</u> for target _ over interval [t1, t2] in which _ is not observed:

$$\mathrm{ECI}_{\_}(t_1, t_2) = \int_{t=t1}^{t2} p(t) \cdot \mathrm{cost}(t2 - t)\,dt$$

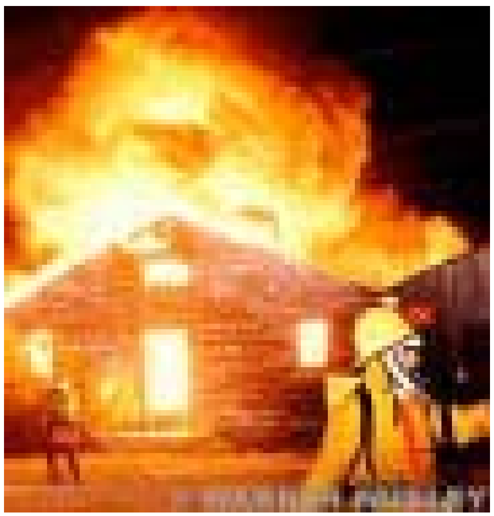
probability density function for event (e.g. fire)

occurrence cost function (e.g. sigmoid)

ECI is the sum for all points in the interval of the probability an event occurs at that point times the cost if it occurs at that point.

Measuring Surveillance Performance

Example



Probability of occurrence (pdf)

$p(t) = ae^{-at}$ ← exponential

sigmoid

Cost if it occurs

$$\mathrm{cost}(d) = c_0 + \left(\frac{2}{1 + e^{-k(d + l_1 + l_2)}} - 1 \right) (m - c_0)$$

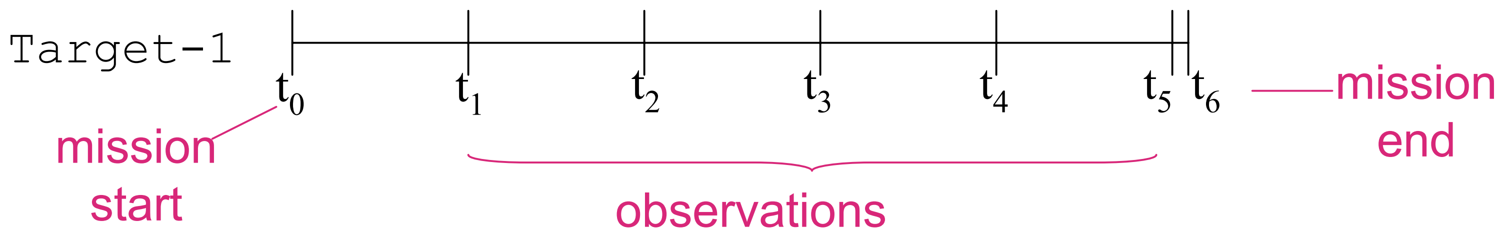
Expected cost of ignorance [t_1 t_2]

$$\mathrm{ECI}_{\_}(\mathrm{t1, t2, a, k, m}) = \int_{t=t1}^{t2} a e^{-at} m\left(\frac{2}{1 + e^{-k(t2 - t)}} - 1 \right) dt$$

AIAA 2004

Measuring Surveillance Performance

The <u>observation timeline</u> for a target specifies at what times (if any) the target was (or will be) observed.



Total mission ECI for one target is the of ECI values for inter-observation intervals (including mission start/end points):

$$\text{target-ECI}\ (\_) = \sum ECI(t_{i-1}, t_i)$$

Measuring Surveillance Performance

<u>Mission-ECI</u>, the total cost of ignorance for all targets accumulated over the mission

$$\text{mission-ECI} = \sum^{\text{targets}} \text{target - ECI}(\tau)$$

The overall surveillance goal is to minimize this value

The value of a <u>surveillance method</u> (algorithm or human operator) in a particular mission is

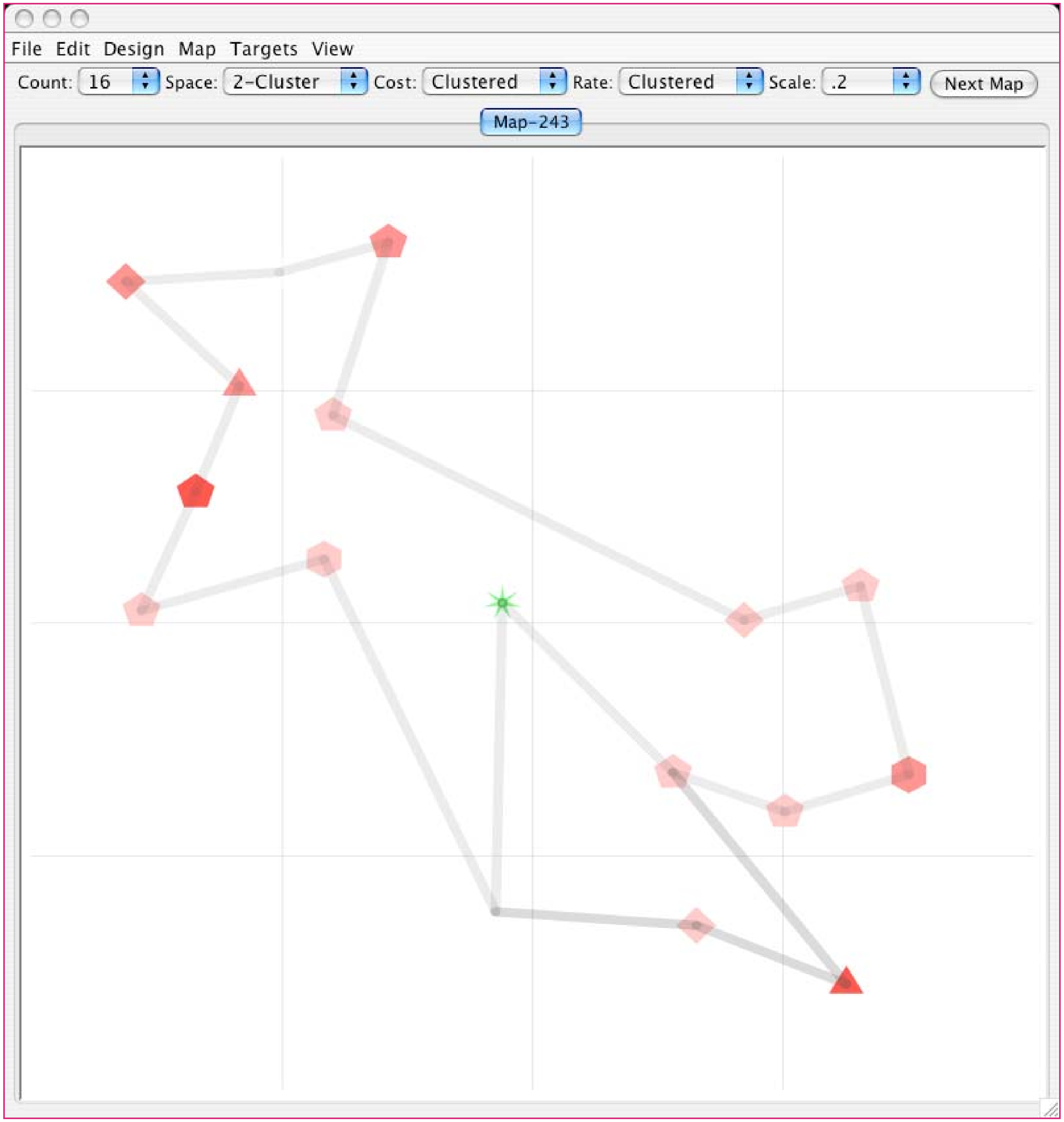
$$\text{Value}_{<\text{method}>} = \text{mission-ECI}_{\text{max}} - \text{mission-ECI}_{<\text{method}>}$$

worst case performance (no observations)

Measuring Surveillance Performance

Goal: know which algorithm to use in a given situation or whether to get help from a human operator

1. Characterize space of possible missions and design representative scenarios
2. Create tool to evaluate performance of human subjects and algorithms in each scenario
3. During operations, dynamically match current situation to closest evaluated mission-type and pick the best “method”

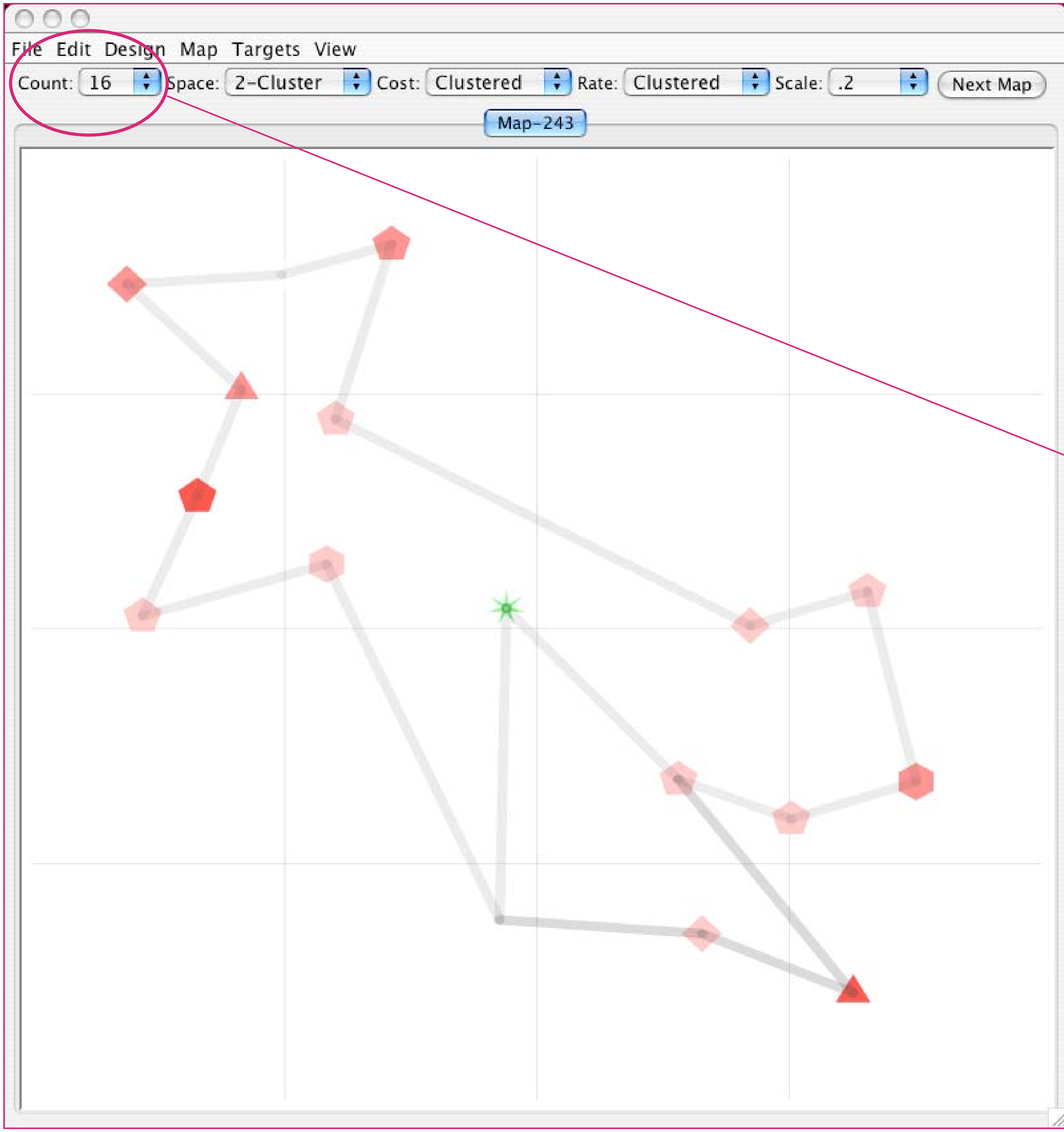


Scenario test set

<u>243 Scenarios</u>

5 dimensions (i.v.'s)

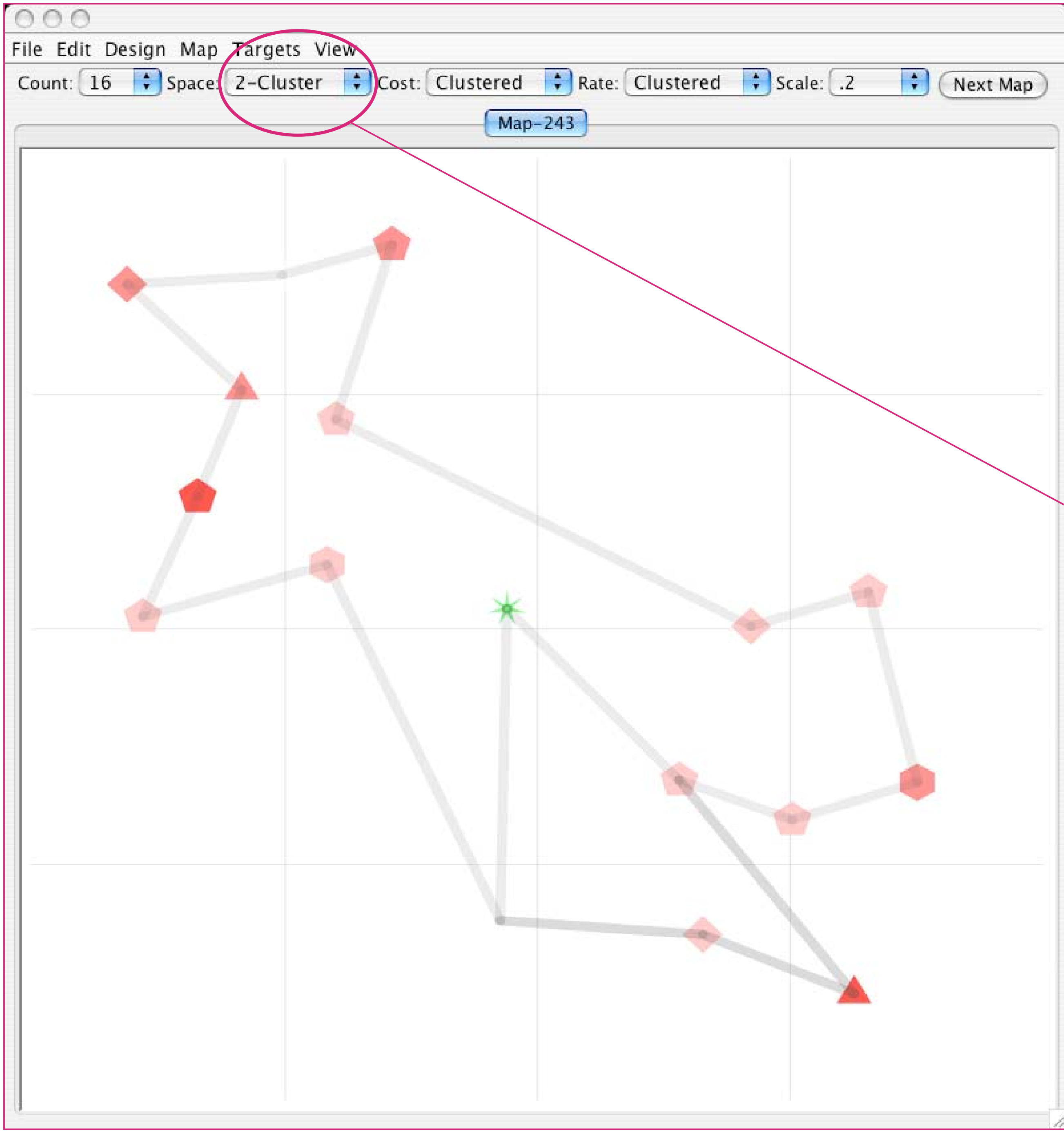
3 values for each



Scenario test set

<u>243 Scenarios</u>
5 dimensions (iv's)
3 values for each

1. Number of targets
   4
   8
   16



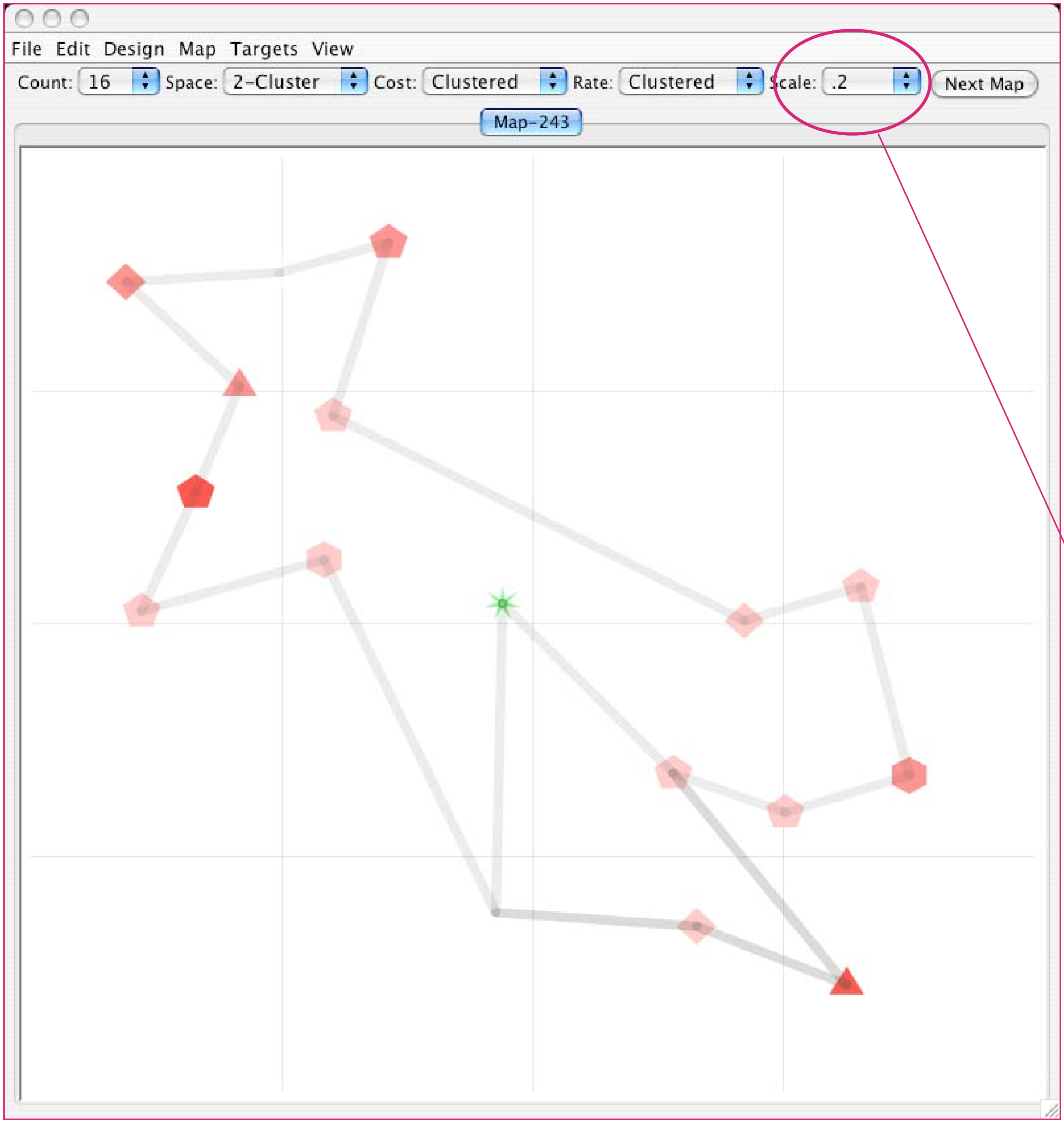
Scenario test set

<u>243 Scenarios</u>

5 dimensions (iv's)

3 values for each

1. Number of targets
2. Spatial Distribution
   uniform
   globular
   clustered



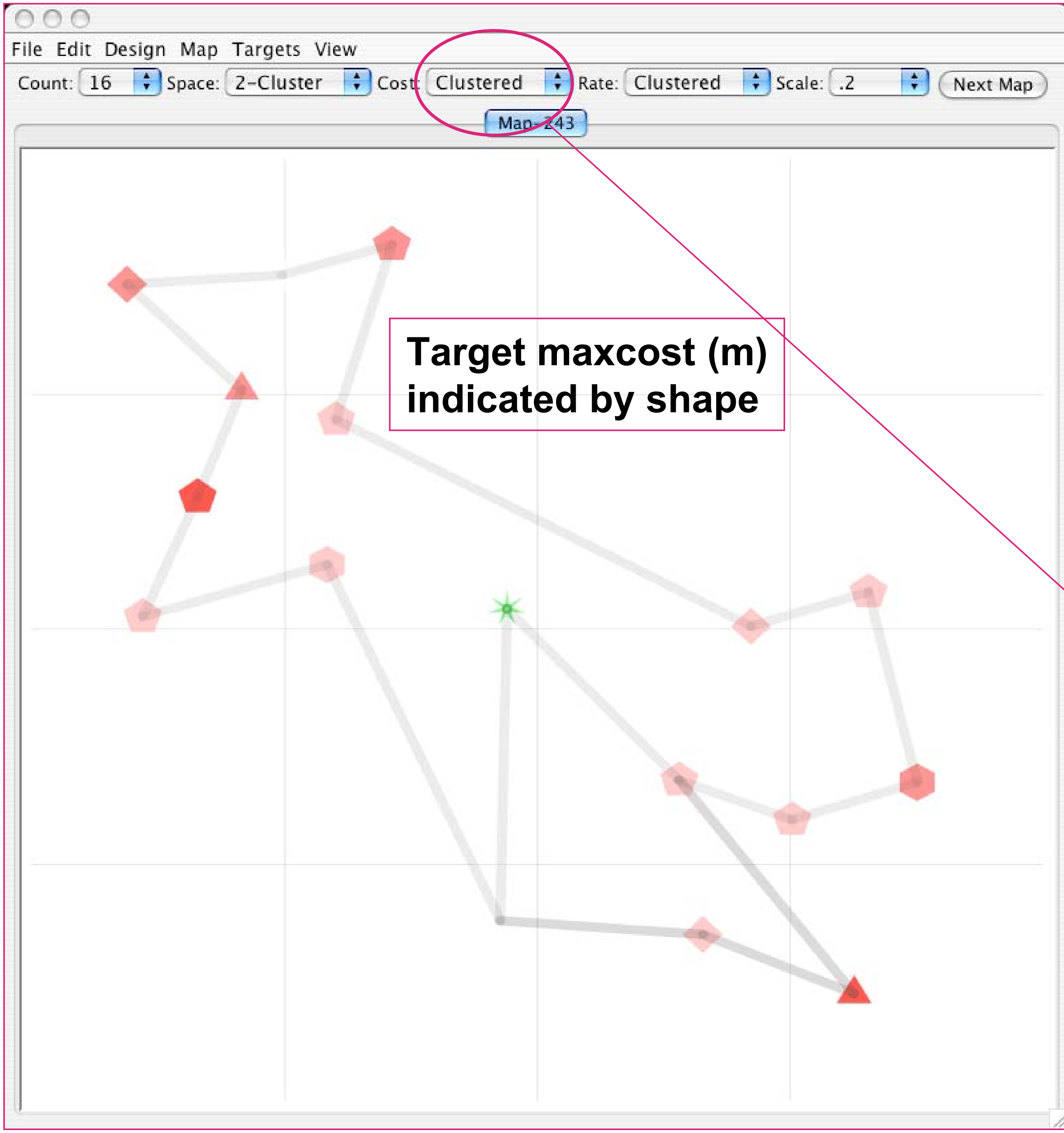
Scenario test set

243 Scenarios

5 dimensions (iv's)

3 values for each

1. Number of targets
2. Spatial Distribution
3. Spatial Scale
   small (.002)
   medium (.02)
   large (.2)



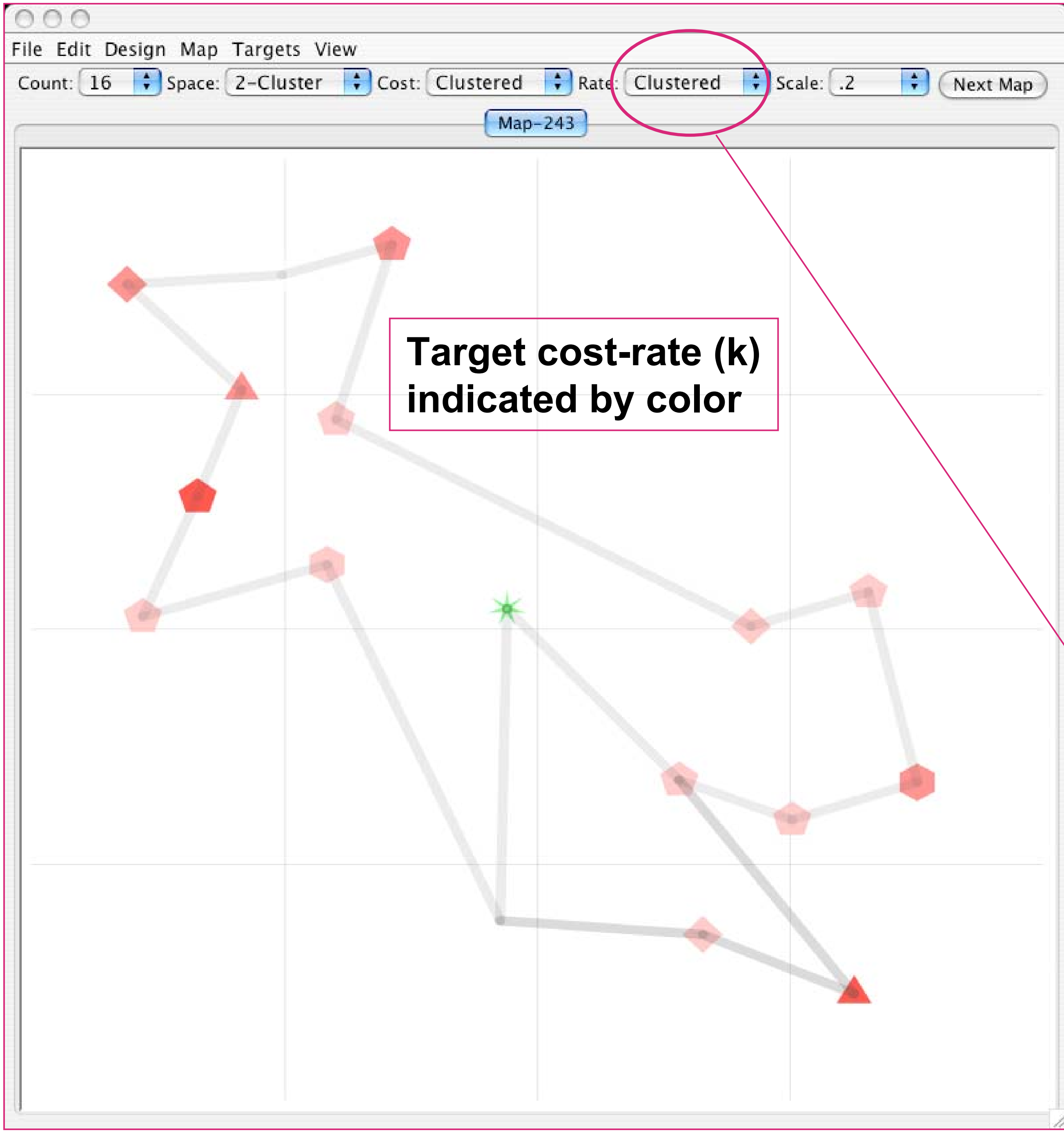
Scenario test set

<u>243 Scenarios</u>

5 dimensions (iv's)

3 values for each

1. Number of targets
2. Spatial Distribution
3. Spatial Scale
4. Maxcost Distribution
   fixed (30)
   uniform (10 20 30 40)
   peaked (30)



Scenario test set

<u>243 Scenarios</u>
5 dimensions (iv's)
3 values for each

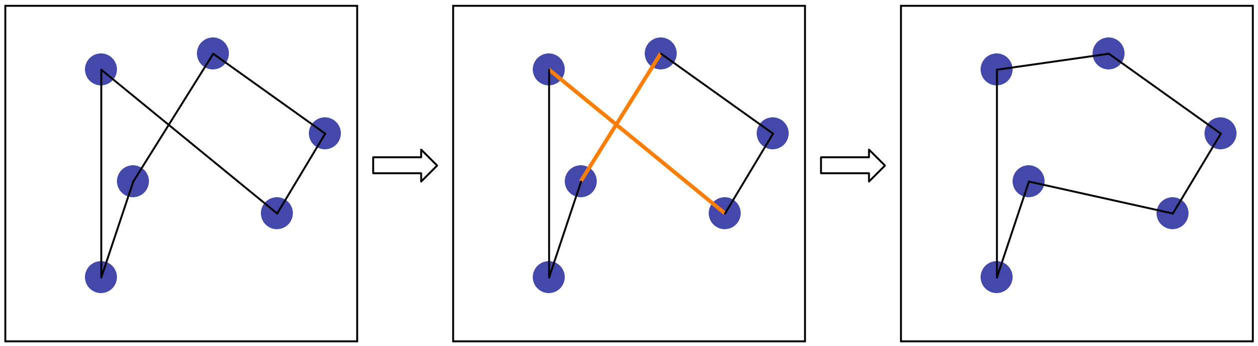
1. Number of targets
2. Spatial Distribution
3. Spatial Scale
4. Maxcost Distribution
5. Cost-Rate Distribution
   fixed (60)
   uniform (20 40 60 80)
   peaked (60)

Comparative Evaluation

Human vs. 2-OPT Algorithm

Modified 2-OPT algorithm

- **Basic 2-OPT computes approximate solutions for TSP**
- **Approach: start with a random tour; iteratively find and apply a tour-improving exchange of 2 tour segments until none found**



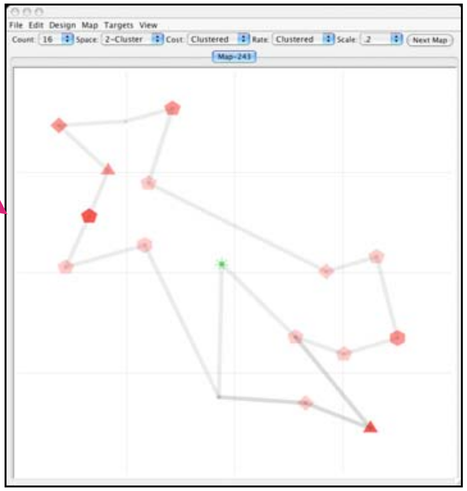
- **Modifications**
  - **Use UAV kinematics model ("smoother") to compute traverse time**
  - **Evaluate return-to-home point given maximum flight duration = 60 minutes**
- **Surveillance performance metric**

Comparative Evaluation

Humans vs. 2-OPT Algorithm

Pilot Study

- Procedure
  - Subject creates/mods/scores tours
  - GUI shows scenario/target attributes
- Test conditions: all 243 scenarios (~6 hrs)
- Surveillance performance metric
- Pilot study
  - 7 subjects so far
  - Training materials, GUI, Decision aids designed to maximize performance, as UAV surveillance expert



Performance Comparison

-- Table shown in proceedings --

Pct. Adv.			N	Spatial							
			4			8			16		
Scale	Rate	Cost	2-Cluster	Globular	Uniform	2-Cluster	Globular	Uniform	2-Cluster	Globular	Uniform
0.002	Fixed	Fixed	0	0	0	0	**14**	0	6	**31**	-3
		Clustered	0	0	0	0	**16**	5	7	**29**	7
		Uniform	0	0	-1	**42**	**24**	5	2	10	**10**
	Clustered	Fixed	0	0	0	0	0	**11**	0	0	**11**
		Clustered	0	0	0	0	0	0	0	0	1
		Uniform	0	0	0	0	0	0	0	0	1
	Uniform	Fixed	**143**	**47**	0	**130**	**19**	**47**	**10**	**93**	**47**
		Clustered	**22**	**28**	**23**	0	**12**	6	3	8	0
		Uniform	**61**	**20**	-2	0	**18**	7	2	5	9
0.02	Fixed	Fixed	0	0	0	1	1	0	0	1	0
		Clustered	0	0	0	1	1	0	0	1	0
		Uniform	0	0	0	1	1	0	1	2	0
	Clustered	Fixed	0	0	0	1	0	0	1	6	0
		Clustered	0	0	0	1	0	0	0	9	1
		Uniform	0	0	0	1	**16**	0	0	6	0
	Uniform	Fixed	0	0	0	1	0	0	2	2	0
		Clustered	0	0	0	1	0	0	2	2	1
		Uniform	0	0	0	1	0	0	0	2	1
0.2	Fixed	Fixed	1	0	0	0	-1	0	-2	**-22**	4
		Clustered	1	0	0	-1	5	-10	-6	**-15**	3
		Uniform	0	0	-1	-2	4	-8	-5	**-19**	4
	Clustered	Fixed	0	0	0	8	0	**14**	9	-1	10
		Clustered	0	0	0	9	-1	**-11**	**11**	**-14**	5
		Uniform	0	0	-1	**16**	8	3	5	**-10**	4
	Uniform	Fixed	3	0	**23**	**14**	-7	**22**	2	-7	**10**
		Clustered	**16**	0	**23**	9	-3	**-12**	9	**-16**	8
		Uniform	**23**	0	**31**	**15**	4	2	-3	**-26**	5

% difference; 1 pilot subject; positive values favor 2-OPT

Pilot Study Summary

- 2-Opt significantly out-performed humans overall ($p < 0.01$)
- Human subjects differed significantly ($p < 0.05$)
- Humans' & 2-Opt's performance strongly correlated ($r > 0.9$)
- Most discriminating i.v. seemed to be Scale
- Least discriminating seemed to be Target-Count
- Humans seemed to do relatively poorly with small-scale maps, small N, low spatial structure (uniform distribution)
- Humans seemed to do relatively well with large-scale maps, large N and high spatial structure (cluster, globular)

Pilot Study Summary

- Humans seemed vulnerable to errors in target-exclusion decisions
- Humans, but not 2-Opt, could benefit from multiple visits to the same target. This is an artifact due to the use of a TSP algorithm rather than a true surveillance algorithm.

Surveillance Algorithms

Scheduling + a bit of planning

- Traveling Salesman Problem (TSP)
- Orienteering Problem
  - Time maximum (visit only subset of targets)
  - Reward varies for individual targets
- Surveillance Problem
  - Repeat visits yield multiple rewards
  - Reward value time-varying
  - Traverse time-cost state-dependent
  - **Reactive version of problem (weather, users)

Ongoing Work

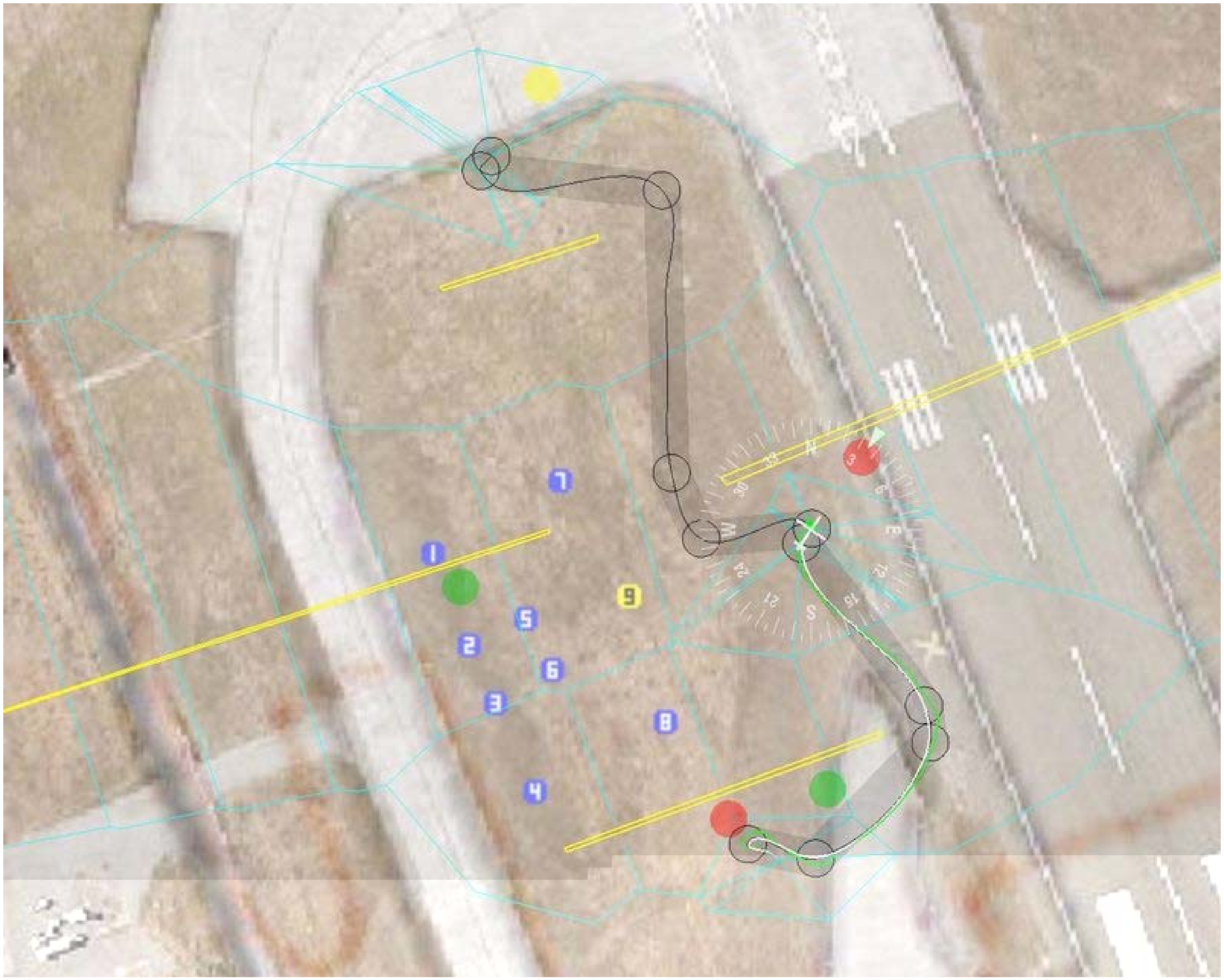
- More and better human subject data (possibly on-line data-collection)
- Expanding testbed (more scenarios, more iv's, more instances of each condition)
- Develop and evaluate true surveillance algorithms
- Distribute testbed to allow others to develop algorithms and test human subjects

Future Work

- Eliciting & maintaining users' utilities/models
- Adjustable autonomy; dynamic algorithm selection
- Handling run-time user requests, changes
- Multiple, heterogeneous surveillance vehicles
- Varied functions: mapping, reconn, search
- Operational integration with human organizations and systems


ariel

Army/NASA Autonomous Rotorcraft Project



Software - Apex

High-level planning/execution

- Runtime tactical planning for camera positioning
- Human-interaction management
- Monitoring and anomaly handling
- Control of specialized problem-solving software (experts)
- Support for creation, explanation and analysis of agent performance
- Obstacle-avoidance path planning
- Flight pattern execution
- Surveillance planning